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No. 352

FUNCTIONING OF REDUCTION GEARS ON AIRPLANE ENGINES

By Raffaelli Matteucci

From "Notiziario Tecnico," December, 1935

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 352.

FUNCTIONING OF REDUCTION GEARS ON AIRPLANE ENGINES.\*

By Raffaelli Matteucci.

In undertaking to analyze the functioning conditions of a reduction gear on an aviation engine, we will consider an ordinary twelve-cylinder V-engine. The reduction gear employed consists either of a pair of spur gears, one of which is integral with the engine shaft and the other with the propeller shaft, or of a planetary system of gears.

Spur-gear system.-- This system has the advantage of great structural simplicity. It renders it possible to place the propeller shaft higher than the engine shaft and to install a cannon or machine gun, so as to fire through the center of the propeller shaft. This system has been employed until very recently by nearly all engine builders. It is generally applied to the end of the crankshaft, though more rarely to the middle. In any case, the pinion attached to the crankshaft must transmit a force which is subject, during the course of each revolution, to periodical variations in intensity. An indication of such variations is given by the final diagram of the tangential forces. It is evident that certain cogs of the pinion (Fig. 1, A', A'', A''') carry heavier loads than the other cogs. Consequently, they wear out faster than the others. It is hardly

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\* From "Notiziario Tecnico," December, 1925, pp. 101-107.

necessary to mention that the wear varies at different points on the same cog and that, with the involute cogs universally employed, there is a very strong scouring action on the head and base of each cog and a tendency to pitting in the central portion and that, by being thus consumed, its shape tends to change from the involute to the cycloidal. This wear, in a reduction gear of the kind under consideration, is quite rapid, due to high specific pressures.

In the case of gears rectified after cementation and hardening, this wear is increased by the diminished hardness of the surface of the cogs and is rendered more irregular by the fact that, during the operation of finishing, a thickness is removed which varies from point to point and that the hardness of the working surface varies correspondingly. It is known, in fact, that the proportion of carbon in the cementation zone diminishes gradually toward the interior.

This unequal wear of the cogs tends to cause periodic vibrations, peculiar to reduction gears in concomitance with the meshing of the more heavily loaded and more worn cogs, and has a marked destructive effect on the driven gear-wheel. When the reduction ratio is such as to cause the frequent meshing of the same cogs, the uneven distribution of the wear on one gear is transmitted to the other gear and the vibrations produced by the meshing are thereby augmented.

In addition to this fundamental and important cause of

poor functioning and distribution in this type of reduction gear, another cause, perhaps still more important, is the torsional vibration to which the crankshaft and pinion are subjected during flight. The crankshaft, under the action of the alternating stresses to which it is subjected by the connecting rods, behaves like a torsional spring, twisting and untwisting periodically. These torsional oscillations are caused either by the transmission of the engine power through each individual crank-web to the pinion of the reduction gear, or by the transmission, from one web to the next, of the compensative stresses which determine the final resultant of the tangential stresses indicated by the cyclic variation of the engine torque.

For example, when the cylinder, which acts on the crank farthest from the wheel of the reduction gear, explodes, the severity of the forces and the magnitude of all the elastic yieldings, manifested in the portion of the crankshaft immediately stressed by the corresponding connecting-rod, are diminished, with regard to the pinion, by the distance and by the inertia of the crankshaft and of the parts rotating with it. On the contrary, when the cylinder explodes, which acts on the crank in the immediate vicinity of the reduction gear, the elastic yieldings cannot take place, without producing a corresponding instantaneous modification in the rotation speed of the gears, i.e., without producing a real shock in the

meshing of the gear-wheels. It is obvious, therefore, that the meshing, already completed under heavy unit loads and under variable stresses periodically distributed on the periphery of the pinion is, moreover, continually disturbed by the torsional vibration of the crankshaft. From this viewpoint, it is better to apply the reduction gear to the end of the crankshaft and not to the middle, as has recently been done by some constructors since, with the latter arrangement, the elastic yieldings of the crankshaft are not diminished so much by the distribution of the compensative forces along the crankshaft. This arrangement, however, does not divide the crankshaft into two separate shafts and the oscillation period of the crankshaft is not affected by the intermediate or terminal location of the reduction gear, nor is the resonance of the engine eliminated or ameliorated. On the contrary, it subjects the gear-teeth to the sudden stresses produced by the four cylinders adjacent to the reduction gear, instead of two cylinders as in the usual arrangement.

Another important cause of vibratory disturbance in the meshing is the oscillation of the two shafts (the crankshaft and the propeller shaft), as shown in Fig. 2. The vibrations of the crankshaft occur in planes which rotate with it and are produced by the elastic deformations of flection and torsion to which it is subjected.

It is only necessary to bear in mind the great lightness

of the engine and its supports and the lightness of the aluminum alloy of which they are composed (an alloy with a very low modulus of elasticity) and the fact that the engine supports are necessarily very short, in order to understand why all these vibrations are so strong. These vibrations are continually changing the alinement of the pinion in all directions with reference to the wheel and consequently the distribution of the load along the cogs, by localizing it on their tips, both when the reduction gear is located at the end of the crankshaft and when it is in the middle.

The vibrations of the propeller shaft are principally caused by elastic deformations in the crankcase produced by the gyroscopic stresses exerted on the shaft by the propeller, as a consequence of deviations in flight. Such deviations are negligible in the horizontal plane, but may reach very high values in the vertical plane, from the effects of pitching and the manipulation of the elevator. The values of these gyroscopic moments, for rather rapid oscillations, are very high and, as a consequence of such high values, the fact is confirmed that, during the evolutions of the aircraft, the latter is supported by the propeller shaft.

This gyroscopic reaction is not constant, however, during every rotation of the shaft. In the case of a two-bladed propeller, since the most sudden oscillations of an aircraft occur in the vertical plane, the gyroscopic action is the greatest at

the instant when the propeller blades are disposed vertically and decreases to about zero when the blades are disposed horizontally. As a consequence of such variations in the gyroscopic forces, the oscillations of the axis of the propeller shaft may frequently assume a vibratory character, which may be transmitted to the propeller itself.

When the reduction gear is located at the head of the engine, the shape of the crankcase is poorly adapted to confer sufficient rigidity on its structure, this condition growing worse in proportion as the reduction ratio is increased. Hence the disalignment of the propeller may become quite large. As regards rigidity, the central position of the reduction gear is much better. This position, however, has the disadvantage of increasing the weight of the engine by lengthening its thickest section and, moreover, does not eliminate all the other causes of disturbance in the meshing of the two gear-wheels. It also diminishes the accessibility.

A few constructors have sought to lessen some of the vibrations by introducing flexible couplings between the crankshaft and the pinion, but encountered great difficulties in the smallness of the available space, the imposed weight limits, the frequent rupturing of the elastic parts, if metal, due to the excessive stresses per cubical unit ( $\text{cm}^3$ ) of the material and from the destructive effect of oil and heat on materials containing rubber.

In short, the inevitable deviations in the parallelism of the axes of the wheels localize the load on the ends of the cogs and represent, in addition to the oscillatory vibrations already mentioned, a second serious source of wear to the cogs.

Planetary reduction gears.— The simplest reduction gears of this type consist of a conical wheel integral with the engine, another conical wheel integral with the crankcase and a train of three or four conical satellite pinions mounted on a supporting ring integral with the propeller shaft.

When it is desired to adopt cylindrical wheels, in order to obtain a practical ratio of reduction (in the vicinity of 2), it is necessary to employ two trains of satellites working in unison and keeping the same position with reference to one another. The best-known reduction gear of this type and the only one, so far as I know, that has yet been used in aviation, is the one used on the Eagle engines made by the Rolls-Royce Ltd. of Derby (England). In this type of reduction gear there are a drive wheel, a system of satellites in two trains, fixed with respect to each other in their rotation, and a stationary wheel integral with the crankcase.

One of the main advantages presented by planetary reduction gears, in comparison with those already considered, is the possibility of avoiding uneven wear of the drive wheel (Fig. 1). If the diameters of the wheels are such that, when the drive wheel is subjected to the maximum torsional stress, the satel-



lites in their successive revolutions do not mesh with the same cogs of the wheel, the wear of the teeth of the driving pinion can be uniform throughout its whole periphery. Referring to Fig. 3, if the cogs  $A'$ ,  $A''$ , and  $A'''$  are subjected to the greatest stress during the first revolution, the cogs  $B'$ ,  $B''$  and  $B'''$  will receive the greatest load during the second revolution,  $C'$ ,  $C''$  and  $C'''$  during the third revolution, etc., the same being true of all the wheels of the mechanism.

The reduction gear on a Rolls-Royce Eagle engine has a device for effectively reducing the vibrations of the cogs. This reduction gear is represented in Fig. 4. No. 1 is the engine shaft at the end of which is fixed a gear-wheel (2) with interior cogs. A series of satellites (3) meshes with said wheel and is supported by means of ball and roller bearings, not shown in the drawing, by a hub integral with the propeller shaft (4). The satellites (3) rotate in unison with a similar series of satellites (5) which mesh with the fixed wheel (6) with exterior cogs. The latter wheel is fixed with reference to the crankcase (7) by means of steel friction disks (8) working in oil and kept continuously under pressure by a series of spiral springs (9). The wheel (6) and the friction disk (8) are subjected to the moment of reaction which naturally follows all the fluctuations of the engine moment. The pressure of the springs (9) is regulated so that, when the engine is functioning under normal conditions, the disks (8) undergo a continuous oscillation, which

evidently takes place in correspondence with the loading points and the torsional vibrations already considered. The friction disks function therefore as a real and efficacious shock-absorbing coupling and the maker justly ascribes to this a great practical value, both for softening the normal stresses and for diminishing any violent shocks due to preignitions and any defects in the functioning of the engine, thus also guarding the aircraft against excessive shocks. This interesting reduction gear is the property of the Rolls-Royce Company, which employs it exclusively on their engines. It is, however, very complicated, expensive and heavy.

The conical shape of the planetary reduction gear enables its rigid attachment to the crankcase, so that the vibrations of the propeller shaft, due to the gyroscopic forces, are largely counteracted.

In short, the causes of poor functioning and rapid wear of reduction gears on aviation engines are very important in reduction gears consisting of a single pair of wheels, but are considerably less in planetary reduction gears. Among the latter and very remarkable, in spite of its complexity, is the one with cylindrical wheels and shock-absorbing disks, made by the Rolls-Royce Company.

Translation by Dwight M. Miner,  
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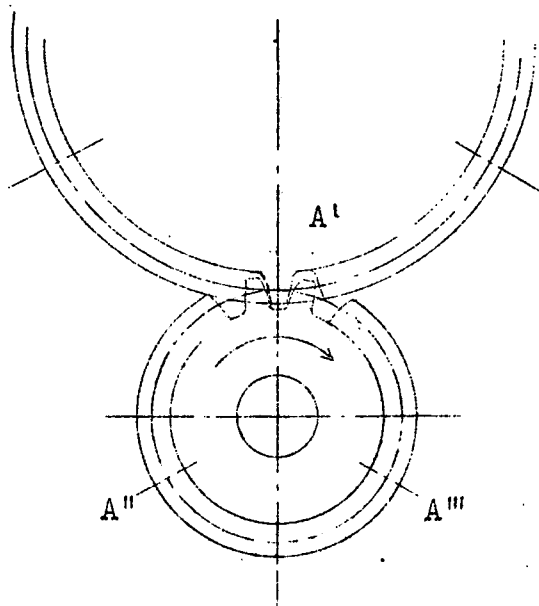


Fig.1

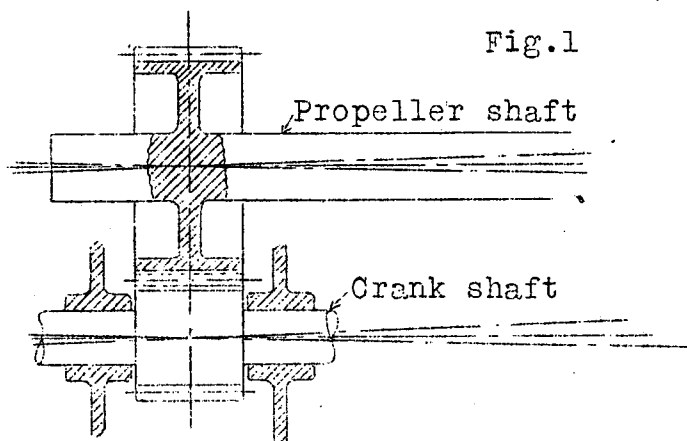


Fig.2

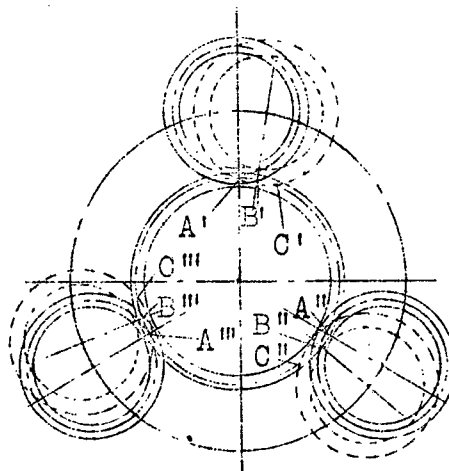


Fig.3

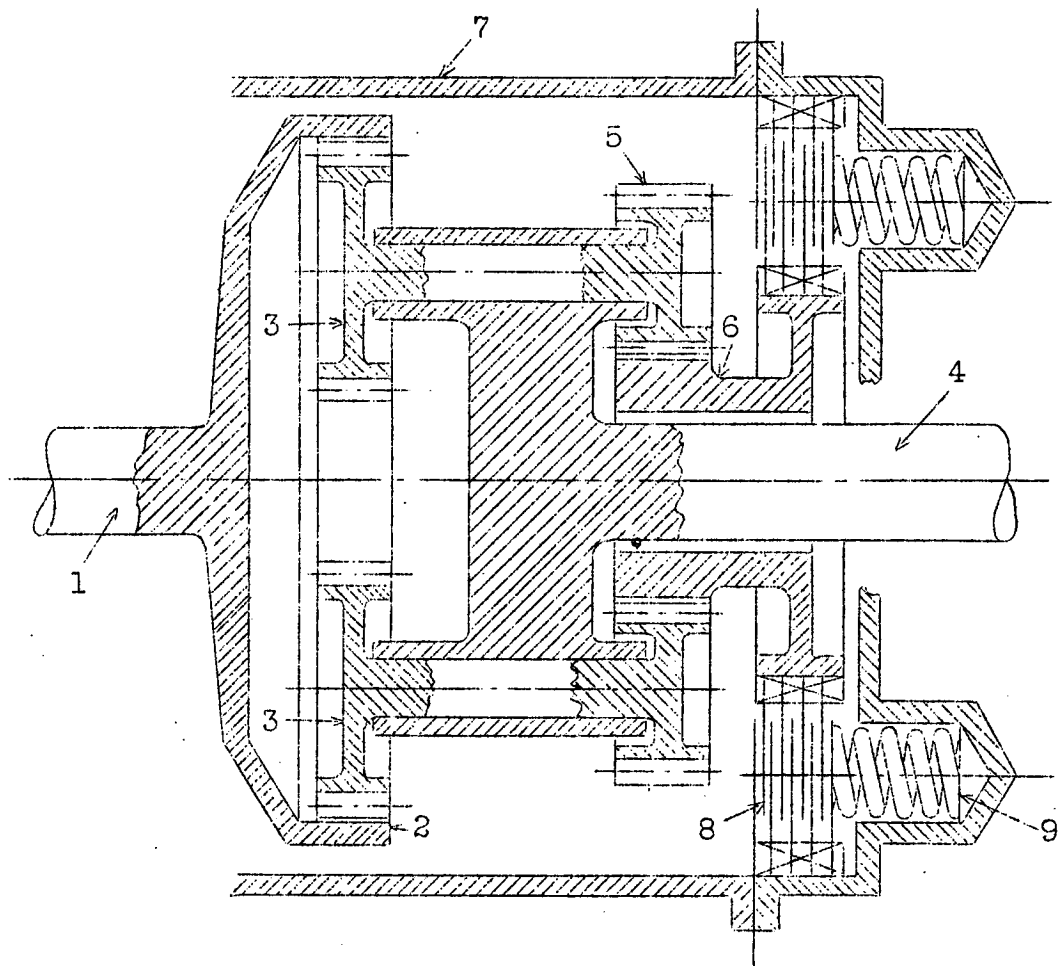


Fig.4